OPTICAL CROSS-CONNECT SWITCH

Related Applications

[0001] This application is a continuation-in-part of commonly-owned U.S. patent application No. 09/842,031 entitled **ABSOLUTE POSITION MOIRÉ TYPE ENCODER FOR USE IN A CONTROL SYSTEM**, filed 26 April 2001, and a continuation of commonly-owned P.C.T. application No. PCT/CA02/00596 entitled **OPTICAL CROSS-CONNECT SWITCH**, filed 24 April 2002. This application claims the benefit of the filing dates of these related applications.

Field of the Invention

[0002] This invention relates to optical switching and control systems for implementing optical signal connections between fibers in optical cross-connect switches.

Background of the Invention

[0003] Digital communications, which may, for example, comprise data, voice or video signals may be carried in optical fibers. It can be desirable to interconnect optical fibers in different ways.

[0004] Optical cross-connect switches include a first group of one or more fibers on a first "side" of the switch and a second group comprising a plurality of fibers on a second "side" of the switch. The first and second "sides" of a switch relate to optical signal transmission pathways and not to a spatial arrangement. Such switches permit a fiber of the first group of fibers to be optically connected with a selected one of the fibers of the second group.

[0005] Optical cross-connect switches typically have control systems which identify two fibers that are to be optically interconnected, and align the fibers to provide an optical connection.

[0006] U.S. Patent No. 5,206,497 discloses an optical cross-connect switch which employs a "one-sided" control system for targeting and alignment. This alignment control system attempts to direct an optical communication signal to a selected target position based on known device geometry and pre-calibrated target positions.

[0007] U.S. Patent No. 6,005,998 discloses a switch comprising two arrays of light beam collimators. The switch comprises two motors with associated encoders to track their positions. The motors tilt a collimating lens on a transmission side of the switch, to direct a beam of a transmission fiber to a pre-calibrated target position on a receiving side of the switch. On the receiving side of the switch, two additional motors control the angle of a similar collimating lens to insert the communication signal into a selected receiving fiber.

[0008] U.S. Patent No. 5,524,153, discloses a switch having a plurality of optical fibers, each housed in a switching unit. LED's are interspersed with the fibers. A control system can identify target fiber within the array of switching units by lighting LED's in a particular pattern to identify the fiber that is to be targeted for connection.

[0009] U.S. Patent Nos. 6,097,858; 6,097,860; and 6,101,299, disclose a switch in which each of a plurality of fibers is housed in a switching unit. Each switching unit is associated with a number of LED's. The LED's emit control signals having a different wavelength from the communication signals. The control signals are used by a control system to make connections between desired pairs of optical fibers.

[0010] Prior art optical switches have various disadvantages including, undesirable complexity, undesirable size, undesirably slow operation, and interference between control signals and communication signals. There remains a need for optical cross-connect switches which avoid or at least reduce some of these problems.

Summary of the Invention

[0011] A first aspect of this invention relates to an optical cross-connect switch for switching optical communication signals between any of a plurality of input optical channels and any of a plurality of output optical channels. The switch comprises a first pattern projector configured to project one or more first control signal radiation patterns and a plurality of output encoders. Each output encoder is associated with one of the plurality of output optical channels. Each output encoder is positioned, relative to its associated output optical channel and the first pattern projector, to receive the first control signal radiation patterns and to detect at least a portion of one or more corresponding output Moiré interference patterns produced by the control signal radiation patterns. Each output encoder is configured to generate a corresponding output control signal indicative of an intensity of detected output Moiré interference patterns.

[0012] The output optical channels may comprise optical fibers.

[0013] Each output encoder may include an associated output reticle with a spatially varying pattern of interaction with radiation incident thereon. The output reticle may be positioned to receive the one or more first control signal radiation patterns and to produce the one or more corresponding output Moiré interference patterns in response thereto. Each output encoder may also comprise an associated output radiation sensor. Each radiation sensor may be positioned to detect at least a portion of the one or more corresponding output Moiré

interference patterns and configured to generate the corresponding output control signal.

[0014] Each of the output reticles may have a spatially varying transmissivity and each associated output radiation sensor may be located to detect radiation from the one or more first control signal radiation patterns that has passed through the associated output reticle. Alternatively, each of the output reticles may have a spatially varying reflectivity and each associated output radiation sensor may be located to detect radiation from the one or more first control signal radiation patterns that has reflected from the associated output reticle.

[0015] Each output reticle may be patterned with a regular array of cells. Each of the cells may comprise an aperture portion and an opaque portion. Alternatively, output reticle may be comprise a circularly symmetric pattern of aperture portions and opaque portions. Each output reticle may pass a first proportion of the first control signal radiation patterns incident on the aperture portion to the associated output radiation sensor and each output reticle may pass a second proportion, smaller than the first proportion, of the first control signal radiation patterns incident on the opaque portion to the associated output radiation sensor.

[0016] Each of the control signal radiation patterns may comprise a plurality of elongated stripes of radiation. Each of the control signal radiation patterns may comprise a spatially periodic radiation pattern. The period of the spatially periodic radiation pattern may be equal to a spatial periodicity of the cells on the output reticles. The cells on the output reticles may be arranged in rows extending substantially parallel to a first axis and columns extending substantially parallel to a second axis and each of first control signal radiation patterns may comprise

elongated stripes which are oriented substantially parallel to one of the first and second axes.

[0017] The control signal radiation patterns may comprise at least one radiation pattern having a first wavelength and at least one radiation pattern having a second wavelength.

[0018] The switch may also include a second pattern projector configured to project one or more second control signal radiation patterns and a plurality of input encoders. Each input encoder may be associated with one of the plurality of input optical channels. Each input encoder may be positioned, relative to its associated input optical channel and the second pattern projector, to receive the second control signal radiation patterns and to detect at least a portion of one or more corresponding input Moiré interference patterns produced by the second control signal radiation patterns. Each input encoder may be configured to generate a corresponding input control signal indicative of an intensity of detected input Moiré interference patterns. The input encoders may have features substantially similar to those of the output encoders.

[0019] The switch may also comprise a controller connected to receive the input and/or output control signals. The controller may be configured to determine a position of each output reticle based on the corresponding output control signal and/or configured to determine a position of each input reticle based on the corresponding input control signal.

[0020] The pattern projector may include an array of first radiation emitting devices located in positions optically opposing the plurality of output optical channels. The first pattern projector may be configured

to project the one or more first control signal radiation patterns by turning on selected pluralities of the first radiation emitting devices.

[0021] Each output encoder may comprise an associated output lens. The output lens may be located to focus the first control signal radiation patterns onto the associated output reticle. Each output lens may also be located to couple optical communication signals from a selected one of the plurality of input optical channels into the associated output optical channel.

[0022] Each output reticle may be coupled to move with the associated output optical channel. The one or more corresponding output Moiré interference patterns may then vary in intensity based on a position of the associated output reticle.

[0023] Each output reticle may alternatively be coupled to move with an associated moveable optical element. A position of each moveable optical element may influence an optical path of an optical communication signal coupled into the associated output optical channel. The switch may comprise a controller coupled to receive the output control signals from the output radiation sensors and configured to determine a position of the moveable optical element based on the corresponding output control signal.

[0024] The switch may comprise a plurality of output actuators. Each output actuator may be associated with one of the plurality of output optical channels. Each output actuator may comprise a magnetic member coupled to move with the associated output optical channel and a plurality of magnetically polarizable branches spaced apart around the magnetic member. The magnetic member may be circularly symmetric. The magnetic member may comprise a ring of magnetic material. The ring may extend around a peripheral edge of the associated output

reticle. Each output actuator may comprise four output branches equally spaced apart around the magnetic member.

[0025] Another aspect of the invention provides an optical switch having a system for independently determining positions of each of a plurality of optical fibers in the optical switch. The position determination system comprises a plurality of reticles, each of which is coupled to move with a corresponding one of the optical fibers. Each reticle has a spatially varying pattern of interaction with radiation incident on the reticle. The position determination system also includes a pattern projector configured to project first and second radiation patterns onto all of the plurality of reticles and a plurality of radiation sensors. Each radiation sensor is associated with a reticle and is located to generate a control signal indicative of an intensity of radiation of the first and second radiation patterns which has interacted with the associated reticle.

[0026] Another aspect of the invention provides a method for coupling an input optical communication signal into an output optical channel selected from among a plurality of output optical channels. The method involves generating one or more output Moiré interference patterns using first control signal radiation. The output Moiré interference patterns vary with a position of a selected moveable output optical element which is associated with the selected output optical channel. The method also involves detecting at least a portion of the one or more output Moiré interference patterns and, based at least in part on the detected portion of the one or more output Moiré interference patterns, determining the position of the selected moveable output optical element.

[0027] Further aspects of the invention, features of specific embodiments of the invention and applications of the invention are described below.

Brief Description of the Drawings

[0028] In drawings which illustrate non-limiting embodiments of the invention:

Figure 1 is a block diagram showing major components of an optical cross-connect switch according to the invention;

Figures 1A to 1C depict various optical cross-connect switch architectures;

Figure 2 depicts a chassis for an optical cross-connect switch according to one embodiment of the invention;

Figure 3 depicts a chassis for an optical cross-connect switch according to an alternative embodiment of the invention;

Figure 4 depicts a scheme of packing control signal RED's between switching units on a chassis;

Figure 5 shows an embodiment of the radiation banks, the radiation stripes and the associated phases on the chassis;

Figure 6 shows a timing diagram indicating the time division multiplexing of control signal pulses from the various phases;

Figure 7 is a cross sectional schematic view of a unit in the plane A-A of Figure 8;

Figure 8 is a schematic diagram of a magnetic actuation system according to an embodiment of the invention in which some parts are omitted for clarity;

Figure 9 depicts a method which may be used to impart a magnetic polarization to the actuator branches;

Figures 10A to 10D show a magnetic actuation system being used to move a fiber end in various directions;

Figure 11 depicts a reticle for use with a two dimensional encoder according to the invention;

Figure 12 is a magnified view of a single cell in the reticle of Figure 11;

Figure 13 shows the reticle of Figure 11 with images of radiation banks projected onto it;

Figure 14 is a schematic diagram of radiation banks according to a simplified embodiment of the invention;

Figure 15 shows the image of one of the simplified radiation banks of Figure 14 on a reticle;

Figure 16 depicts a spatial variation of the measured intensity signals associated with each of the three phases in one of the radiation banks;

Figure 17 depicts the spatial variation of a particular phase in one of the radiation banks in two distinct regions of the reticle;

Figure 18 is a schematic diagram that depicts communication signals being focused and transmitted across a switch interface;

Figure 19A depicts a circular reticle in accordance with a particular embodiment of the present invention;

Figure 19B depicts a radiation bank embodiment that may be used with the circular reticle of 19A; and

Figure 20 depicts the image of a radiation bank and its associated RED's on the surface of a dual wavelength reticle.

Description

[0029] Throughout the following description, specific details are set forth in order to provide a more thorough understanding of the invention. However, the invention may be practiced without these particulars. In other instances, well known elements have not been shown or described in detail to avoid unnecessarily obscuring the invention. Accordingly, the specification and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

[0030] This invention relates to optical cross-connect switches and alignment control systems for such switches. The invention may be applied to $M \times N$ type switches in which any one of a first set of M optical fibers may be placed in optical communication with any one of a second set of N optical fibers. Figure 1 shows an example of a switch **200** that includes a first set of optical fibers which includes a first optical fiber **202** and a second set of optical fibers which includes a second optical fiber **204**. Switch **200** has an alignment control system **206**. Alignment control system **206** identifies one of the M first fibers to be optically connected to one of the N second fibers. Alignment control system **206** may receive commands from an external source. The commands identify pairs of first and second optical fibers to place into optical communication with one another. An actuation system **208** comprises an actuator **209A**, which directs a selected one of the M first fibers into alignment with a selected one of the N second fibers and an actuator **209B**, which directs the selected one of the N second fibers into alignment with the selected one of the M first fibers. A position measurement system **210** includes position sensors associated with each of the M first fibers and each of the N second fibers. Position sensor **211A** is associated with fiber **202** and position sensor **211B** is associated with fiber **204**. Alignment control system **206** receives information from position measurement system **210** and uses this information to determine actuator signals, which are sent to actuation system **208**, so that the alignment of the selected one of the M first fibers and the selected one of the N second fibers may be accomplished in a controlled manner.

[0031] Alignment control system **206**, actuation system **208** and position measurement system **210** may share components

[0032] In this disclosure, “light” and “radiation” are used interchangeably. “Light” is not limited to visible light and includes electromagnetic radiation of any suitable wavelength.

[0033] Figures 1A-1C are schematic representations of possible configurations for an $M \times N$ switch. Figures 1A-1C show 16×16 switches. Switches according to this invention may have fewer fibers or many more. For example, a switch according to the invention may be 1024×1024 or even larger.

[0034] Figure 1A illustrates a switch **10** having an opposing chassis configuration. Switch **10** comprises a first chassis **16** located directly opposite to a second side chassis **18**. A plurality of first fibers **12** are mounted in first chassis **16**. Each first fiber **12** may be optically connected to one of a plurality of second fibers **14** in second chassis **18**. Once made, the optical connection between a first fiber **12** and a second fiber **14** can carry an optical communication signal. "Communication signal" means a light beam which can be modulated to carry data of any kind. A communication signal may be bi-directional. Communication signals may include, without limitation, zero modulation signals that result in a constant wave optical beam. Typical communication signals have wavelengths of $\lambda = 1310$ nm and $\lambda = 1550$ nm. However, a switch according to the invention may handle communication signals of any wavelength.

[0035] First chassis **16** and second chassis **18** are separated by a transmission cavity **20**. Preferably, transmission cavity **20** is relatively empty, so that communication signals can be transmitted between any of first fibers **12** and any of second fibers **14**. Each of fibers **12** and **14** is associated with a switching unit **22**.

[0036] Each switching unit **22** comprises a lens (not shown in Figures 1A to 1C), which shapes the radiation beams of communication signals emanating from (or entering) the corresponding fiber **12** or **14**.

[0037] Figure 1B shows a switch **10'** which has a flat mirror **17** located so that any fiber **12'** on chassis **16'** may be optically connected with any one of fibers **14'** on chassis **18'**. The folded optical pathway indicated generally by phantom line **15** illustrates a typical optical path for a communication signal associated with such a connection. A switch may be implemented using multiple folds in the optical pathway, so as make the switch **10'** conform to the required physical dimensions.

[0038] Figure 1C shows a switch **10"**, which employs a single chassis **16"** facing a flat mirror **17'**. Switch **10"** comprises first and second groups of switching units **19** and **21** that are both located on a single chassis **16'**. This configuration can also be used to make switch **10"** compact. Although only three configurations have been described, it will be appreciated that using simple optical elements, many possible configurations can be implemented, provided that these configurations allow for optical path connection between fibers.

[0039] In this disclosure, two fibers in a switch are on "different sides" if the switch can optically couple the two fibers. A "side" may transmit or receive optical communication signals, or both, and is not necessarily physically distinct from or adjacent to the opposing "side".

[0040] Each fiber has an associated actuator **209**. Actuators **209** are controlled by alignment control system **206**. Alignment control system **206** operates the actuators of selected pairs of fibers to facilitate the transmission of optical communication signals between the fibers of each selected pair. Alignment control system **206** may receive information specifying alignments of the fibers from a position measurement system **210**.

[0041] Figure 2 depicts two Cartesian axes **x** and **y**. Positions of the ends of fibers **12**, **14** are described herein as being specified relative to these axes. The axes **x** and **y** are not uniquely chosen. Other coordinate systems could be used to describe locations of the ends of fibers **12**, **14**.

[0042] Each switching unit **22** of Figure 2 comprises a lens **25** (see Figure 7), which focuses radiation entering or exiting the switching unit **22**. Lens **25** may comprise any combination of one or more optical elements that achieves the functional goals described herein. In typical operation, lens **25** receives communication signals from a fiber on the other "side" of the switch and focuses the communication signal on the fiber end **12'**. Where switching unit **22** has a fiber **12** that is transmitting communication signals, lens **25** focuses outgoing communication signals from the fiber end **12'**.

[0043] Figures 18A and 18B depict schematically the transmission of a communication signal beam across the switch interface. Extraneous elements, such as bending mirrors and other switching unit elements are omitted in Figures 18A and 18B. In order to reduce optical losses, it is preferable (but not necessary) that the communication signal be a focused beam (as opposed to a collimated beam susceptible to divergence). Communication signals from the end **400** of the core of a first side fiber **402** are focused by lens **25** forming a beam **405**, which has a "waist" in the switch interface cavity and which is directed substantially onto the surface of the second side lens **25'**. Second side lens **25'** receives the communication signal beam **405** and distributes it across the end **408** of the core of second side fiber **410**. In a similar manner, a focused communication signal beam **407** may be transmitted from the second side fiber **410** to the first side fiber **402** as depicted in Figure 18B.

[0044] Figure 7 depicts a switching unit **22** according to one embodiment of the invention. Switching unit **22** comprises an actuation system **49**, one embodiment of which is further depicted in Figures 8 and 9. Referring to Figures 7-9, actuator system **49** employs magnetic fields to position the ends **12'** of an individual fiber **12** in two dimensions. Actuator system **49** comprises a magnetic member **50** connected to move with end **12'** of fiber **12**. Member **50** is preferably circularly symmetrical and may comprise a ring of a magnetic material such as a metal. Magnetic member **50** may comprise a ferrite material (such as an alloy comprising of nickel and iron).

[0045] Member **50** interacts with magnetic fields developed by actuator branches **41A**, **41B**, **41C** and **41D** (collectively, actuator branches **41**). In the illustrated embodiment, the individual actuator branches **41A**, **41B**, **41C** and **41D** are positioned so as to be substantially symmetrically located between the **x** and **y** axes. In such an embodiment, the center of each individual actuator branch (**41A**, **41B**, **41C** and **41D**) is located at approximately 45 degrees between the **x** and **y** axes.

[0046] Actuation system **208** (see Figure 1) provides actuator signals **48A**, **48B**, **48C** and **48D** (collectively, actuator signals **48**). Actuator signals **48** magnetically polarize actuator branches **41** by passing electrical current through windings (not shown) in actuator branches **41**. Branches **41** may be made of a ferrite material. Other materials may also be used. By varying the magnetic polarization of individual branches (**41A**, **41B**, **41C** and **41D**) actuation system **208** can cause magnetic member **50** to move and to carry end **12'** of the corresponding fiber to a desired "target" position.

[0047] In the illustrated embodiment, member **50** comprises a ring which extends around the periphery of a transparent disk **44**. Fiber end **12'** is mounted to disk **44**. Switching unit **22** comprises a reticle **30** for a position measurement system. Advantageously, reticle **30** is mounted behind transparent disk **44**.

[0048] The interaction between actuator branches **41** and member **50** may be understood by referring to Figures 9A and 9B, which schematically depict a portion of the actuator branches **41A** and **41B** with respective coils **46A** and **46B** wrapped around them. Actuator signal **48A** controls the magnitude of a current supplied by current source $\mathbf{I_A}$ and, similarly, actuator signal **48B** controls the magnitude of a current supplied by current source $\mathbf{I_B}$. When current passes through coil **46A**, a magnetic field is generated and the actuator branch **41A** is polarized. The active end **41A'** of actuator branch **41A** acquires a magnetic north polarization. Similarly, when current passes through coil **46B**, a magnetic field is generated, actuator branch **41B** is polarized and the active end **41B'** of actuator branch **41B** acquires a magnetic south polarization. The strength of the magnetic fields associated with the polarization of active ends **41A'** and **41B'** of actuator branches **41A** and **41B** is controlled by the amount of current that flows through coils **46A** and **46B**.

[0049] Each of Figures 10A through 10D show a plan view of the end of a switching unit **22**. Figure 10A shows how the actuator branches **41A** and **41B** are polarized to move member **50** in the positive *y* direction (indicated by arrow **52A**). Actuator branch **41A** is polarized to be a north magnetic pole and actuator branch **41B** is polarized to be a south magnetic pole. In a manner similar to that of a conventional horseshoe magnet, the polarization of actuator branches **41A** and **41B** creates a magnetic flux (indicated by arrows **51)** which draws member **50** (and hence the fiber end **12'** (see Figures 7 and 8)) in direction **52A**.

[0050] Figure 10B shows how actuator branches **41B** and **41C** are polarized to move member **50** in the positive *x* direction by polarizing branches **41B** and **41C** to be south and north magnetic poles respectively. This polarization creates force, which moves member **50** and the fiber end in the positive **x** direction indicated by arrow **52B**.

[0051] Figure 10C shows branch **41A** with a north polarization and branch **41D** with a south polarization, so as to move member **50** in negative *x* direction **52C**. Figure 10D shows branch **41C** with a north polarization and branch **41D** with a south polarization, so as to move member **50** in negative *y* direction **52D**. By using linear combinations of the above described configurations, actuator system **49** can move member **50** and fiber end **12'** in any direction on the two-dimensional plane of the **x** and **y** axes.

[0052] The design of the actuation system overcomes some difficulties associated with prior magnetic-based fiber bending actuation systems. The design maximizes the transverse magnetic flux, and corresponding force, experienced by member **50** in the two-dimensional plane spanned by the **x** and **y** axes, while minimizing forces that tend to tilt or rotate member **50**. The design also reduces cross-talk between actuation systems in adjacent switching units **22**.

[0053] Actuator branches **41** may be situated quite close to one another to make switching unit **22** compact. It is desirable to reduce the amount of magnetic flux which jumps directly between two polarized branches. Flux lines that jump directly between branches **41** do not contribute to the movement of member **50** and represent losses of power. For example, in Figure 10-A, it is desired for the magnetic flux (indicated by arrows **51**) to emanate from actuator branch **41A**, pass through member **50**, and then pass from member **50** into actuator branch **41B**. To minimize the parasitic loss of flux, actuator branches **41** may

be designed to be as short as possible, as far apart as possible and to have an optimal surface curvature, while still capable of being polarized at or near the magnetic saturation of the branch material. Member **50** may comprise a ring, which is wide along the **z**-axis (see Figure 8), so as to maximize its surface area capable of receiving magnetic flux. Reducing the amount of magnetic flux which jumps directly between two polarized branches helps to minimize the switching time for a given power consumption.

[0054] The "cup" shaped curvature of actuator branches **41** and the cylindrical shape of member **50** help to minimize the torques that tend to cause second order bending (i.e. bending in an "S-shaped" mode) of fiber **12** and/or rotation of member **50** about the **z** axis). The cup shape of branches **41** helps to create a force on member **50** that has no appreciable components oriented along the **z**-axis. The cylindrical shape of member **50** ensures that there is circumferential symmetry and that there are no torques that might cause member **50** to rotate about the z-axis. The length of actuator branches **41** and the corresponding length of bare fiber **12** can be chosen to compensate for the possibility of mechanical resonance.

[0055] Where switching units **22** are small, only small movements are required of actuation system **49**. This permits actuation system **49** to have reduced power consumption and fast switching times. Magnetic actuation system **49** can be designed for operation with voltages lower than voltages required by piezoelectric actuation systems.

[0056] Piezoelectric, mechanical or micro-mechanical means could also be used to move the ends of optical fibers in a switch according to some embodiments of this invention. Alternatively, an alignment control system according to some embodiments of the invention may be implemented by inserting moveable optical elements, such as

micro-electro-mechanical system (MEMS) mirrors into the paths of communication signals to direct the communication signals between fibers.

[0057] During typical switch operation, alignment control system **206** (see Figure 1) receives an externally generated network command requesting that a particular switching unit **22** be configured to receive communication signals from a switching unit **22** on the opposite "side" of the switch. In the embodiment of Figure 7, alignment control system **206** comprises a controller **47**. The term "controller" (i.e. controller **47**) includes all processors capable of providing the functionality described herein and includes, without limitation, embedded microprocessors, dedicated computers, groups of data processors or the like. Controller **47** may also be shared with other systems, including actuation system **208** and position measurement system **210** (see Figure 1). In order to optimise the reception of such communication signals, fiber end **12'** must be moved in two dimensions to a "target position", where the insertion of the communication signal into the core of fiber end **12'** is maximized. The two dimensions of movement of fiber end **12'** are in the plane substantially perpendicular to the page of Figure 7. Movement of fiber end **12'** is controlled by alignment control system **206** and controller **47**.

[0058] A fiber position measurement system **210** (see Figure 1) determines the current position of fiber end **12'**. Prior to receiving the externally generated network command, fiber **12** will typically be out of alignment (i.e. the actual position of fiber end **12'** will be different from the target position). Using the target position of fiber end **12'** and current and previous measurements of the actual position of fiber end **12'**, controller **47** uses control theory techniques to generate actuator signals **48**. Depending on timing requirements and controller resources, alignment control system **206** may cause the actuation system to run

"open loop" for an initial period during large jumps (i.e. where the target position is significantly different than the actual position). In open loop mode, controller **47** sets actuator signals **48** at levels that are independent of the actual position of fiber end **12'**.

[0059] After a brief period of open loop operation, alignment control system **206** resumes control of actuator signals **48** using positions measured by position measurement system **210** for feedback. When the actual position of fiber end **12'** reaches the target position, controller **47** is said to be "servo-locked" on the target position. Once servo-locked on the target position, any small deviations of the actual position from the target position may be rectified by controller **47**.

[0060] Although the above discussion describes alignment control system **206** from the perspective of a particular switching unit **22**, it should be appreciated that control of the transmitting and receiving fiber ends occurs simultaneously in the associated switching units **22** on both "sides" of the switch. That is, alignment control system **206** controls the position of the fiber end in the transmitting switching unit to optimise the direction of the transmission of communication signals to a particular receiving switching unit on the other "side" of the switch. Simultaneously, alignment control system **206** controls the position of the fiber end in the receiving switching unit to optimise the reception of the communication signal from a particular transmitting switching unit on the other "side" of the switch. For this reason, alignment control system **206** disclosed herein may be said to be a "two-sided" control system as opposed to some of "one-sided" prior art control systems. A two-sided control system has the advantage of increasing the effective numerical aperture of the receiving fibers. In addition, two-sided control can compensate for small movements of components on either side of the switch.

[0061] Position measurement system **210** may comprise a two-dimensional "Moiré type" position encoder associated with each switching unit **22** and each fiber **12**. To measure a position of their associated fiber, the encoders use optical position signals from radiation sources, which may be mounted on the opposing "side" of the switch. The same optical position signals may be used by encoders for all switching units **22** on one side of the switch. The two-dimensional position encoders may be as disclosed in the related application described above, which is hereby incorporated by reference.

[0062] Position measurement system **210** operates by projecting radiation patterns onto reticles **30**, which move with the ends **12'** of fibers **12** (see Figure 7). Photodetectors **24** in each of switching units **22** detect the intensity of radiation from the projected radiation patterns after they have interacted with corresponding reticle **30**. In switching unit **22** of Figure **7**, the radiation patterns are imaged by lens **25** through transparent disk **44** and onto reticle **30**. The portion of the radiation that is transmitted through reticle **30** is then collected by light pipe **43**, which internally reflects the radiation as it is directed toward mirror **42**. Mirror **42** reflects the radiation toward a photodetector **24**, which measures the intensity of the radiation and delivers an electronic signal to controller **47**. The radiation patterns are preferably projected onto outer portions of reticle **30** away from fiber end **12'**.

[0063] Transparent disk **44**, light pipe **43** and mirror **42** are not fundamental to the invention. In general, the invention should be understood to incorporate any optical means of collecting the radiation transmitted through reticle **30** and directing it towards photodetector **24**.

[0064] The radiation patterns may be provided by radiation sources located on each "side" of the switch. The radiation sources preferably emit radiation at wavelengths different from wavelengths used for communication signals and may, for example, comprise radiation emitting devices (referred to herein as RED's), such as light-emitting diodes, laser diodes, or other types of devices that emit detectable radiation. The radiation sources may, for example, emit light having a wavelength of $\lambda=940$ nm where communication signals have wavelengths of $\lambda=1310$ nm or $\lambda=1550$ nm.

[0065] Photodetectors **24** are preferably sensitive to the radiation emitted by REDs **11**, but not to the communication signals. For example, photodetector **24** may comprise a conventional Si photodetector, which is sensitive to radiation at $\lambda=940$ nm and not sensitive to communication signals at longer wavelengths such as $\lambda=1310$ nm or $\lambda=1550$ nm.

[0066] Figure 2 depicts a plan view of a chassis **16** representing one "side" of an optical switch in accordance with a particular embodiment of the invention. The other "side" of the switch (not shown in Figure 2) has a chassis substantially similar to that of Figure 2. Chassis **16** of Figure 2 depicts a possible layout of the control signal RED's **11** and switching units **22**. Figure 2 shows that the control signal RED's **11** are arranged into four groups (**21A**, **21B**, **21C** and **21D**), which are referred to as "radiation banks" (collectively, radiation banks **21**).

[0067] RED's **11** are not associated with any particular switching units **22** or any particular fiber **12**. RED's **11** are collectively associated with the fiber position measurement for all of a plurality of switching units **22** on the other "side" of the switch. RED's **11** may be located separately from switching units **22**, provided that they are in

optical communication with switching units **22** on the other “side” of the switch.

[0068] An implementation having control signal RED’s **11** that are separated from switching units **22** is depicted in Figure 3. Figure 3 depicts two optically opposed chassis **16** and **18**, which house switching units **22**. Each chassis **16** and **18** has a separate component **16'** and **18'**, which contains RED’s **11**. The control signals from RED’s **11** on chassis component **16'** are reflected onto the face of chassis **18** by mirror **17**. Similarly, control signals from RED’s **11** on the chassis component **18'** are reflected onto the face of chassis **16** by mirror **17**. Because individual RED’s **11** are not associated with any particular switching units **22** or fibers **12** or **14**, there are many possible arrangements of RED’s **11** in combination with lenses, mirrors and/or other optical elements capable of achieving the required functionality.

[0069] In the embodiment illustrated in Figure 2, individual control signal RED’s **11** in radiation banks **21** are packed between switching units **22** to minimize the size of chassis **16** and the overall size of the switch. In the regions of radiation banks **21**, each RED **11** is packed between four adjacent switching units **22**.

[0070] Figure 4 is a close up view of a number of switching units **22** and RED’s **11** on chassis **16** in the region of radiation bank **21A**. The arrangement of Figure 4 is not the only scheme for closely packing control signal RED’s **11** and switching units **22**. The invention should be understood to incorporate other simple packing schemes designed to maximize the number of switching units **22** and maintain a sufficient number of control signal RED’s **11** on a two dimensional chassis surface. The dimensions of switching units **22** may vary from implementation to implementation or even as between individual switching units **22** within a particular switch.

[0071] The chassis of Figure 2 has three regions **23** oriented along the **y** axis, where there are no switching units **22**. These regions **23** may be used for mounting chassis **16** to the body of the switch, mounting switching units **22** to chassis **16** and, to house calibration sensors **26**, which are employed to calibrate the alignment control system **206** prior to use. Calibration sensors **26** may comprise photodetectors which are sensitive to the wavelengths of the communication signals but not to the wavelength of the RED's. For example, calibration sensors **26** may comprise Germanium photodetectors which can detect light having wavelengths of $\lambda=1310$nm and $\lambda=1550$ nm, but not light having a wavelength of $\lambda=940$ nm.

[0072] In a calibration procedure light directed through each fiber may be directed on the calibration sensors **26**, which act as targets. With a knowledge of the sensor location (i.e. on chassis **16**) with respect to the location of switching units **22**, the system can be calibrated.

[0073] Figure 5 depicts chassis **16** and RED's **11** of a particular embodiment of the invention. Switching units **22** are not shown in Figure 5. The fiber position measurement system **210** may be implemented with two or more radiation banks **21**. A currently preferred embodiment of the invention comprises four radiation banks (**21A**, **21B**, **21C** and **21D**).

[0074] Each radiation bank **21** comprises several spatially periodic groups of radiation stripes (**A** through **L**) made up of rows or columns of RED's **11**. The individual radiation stripes of radiation banks **21** have an elongated shape and are said to be "oriented" along a particular axis if their elongated shape is substantially parallel to that axis. Radiation bank **21A** comprises spatially periodic groups of radiation stripes **A**, **C** and **E** oriented along the **x**-axis. Radiation bank **21B** contains groups **G**, **I**, and **K** of radiation stripes which are oriented

along the y-axis. Radiation bank **21C** contains groups **B**, **D** and **F** of radiation stripes oriented along the **x**-axis. Radiation bank **21D** contains groups **H**, **J**, and **L** of radiation stripes which are oriented along the y-axis.

[0075] The embodiment of Figure 5 shows radiation banks **21** each having three spatially-periodic groups of radiation stripes with each radiation stripe made up of a plurality of RED's **11.** In general, radiation banks **21** may comprise any number of groups of radiation stripes and each radiation stripe may incorporate any radiation source. The use of individual RED's **11** to form the radiation stripes facilitates compact switch geometries. In alternative embodiments, such as the embodiment of Figure 3, other radiation sources, such as liquid crystal light valves illuminated by conventional light sources, may be used to implement the individual radiation stripes.

[0076] A controller causes each group of radiation stripes (**A** through **L**) to generate pulses of radiation. Radiation signals (**A** through **L**) from the pulsing of radiation stripes (**A** through **L**) are referred to as "phases" herein. In preferred embodiments, the pulses of phases (**A** through **L**) are multiplexed in time. A possible sequence for pulsing phases **A** through **L** is depicted in Figure 6. The timing of the pulses may be controlled by a central clock signal, which is available on both "sides" of the switch. Thus, when controller **47** receives a signal indicating the intensity of radiation detected at a photodetector **24** at a specific time (see Figure 7), controller **47** can use the central clock signal to associate that intensity with a particular phase (**A** through **L**). Periodically, for example, after each phase (**A** through **L**) has been pulsed once, there is a period $\mathbf{t_o}$ where no phases are pulsed. Period $\mathbf{t_o}$ may be used to measure background ambient light levels for use in normalizing the measured intensities of phases (**A** through **L**).

[0077] In this disclosure, the letters (**A** through **L**) are used to designate: groups of radiation stripes; optical control signals emitted by the radiation stripes; and electronic signals measured when the optical control signals are sensed by photodetectors **24**.

[0078] Controller **47** receives timing information from the central system clock. Using this timing information and the electronic signals from photodetector **24**, controller **47** is able to separately detect the intensity of radiation from each phase (**A** through **L**) that is transmitted through reticle **30**. Controller **47** can determine the two dimensional position of reticle **30** (and fiber end **12'**) from the measured intensities for the different phases and known properties of reticle **30**.

[0079] Figure 11 depicts reticle **30**, which may be used in a position measurement system to provide absolute positional information about the location of a fiber end **12'**. Reticle **30** is a two-dimensional reticle with axes labelled **x** and **y**. Each cell **34** of reticle **30** has two distinct regions, a substantially transparent aperture **32** and an opaque or non-transmissive region **33**. Each cell **34** of reticle **30** has a length $\mathbf{L_x}$ on the **x**-axis (referred to herein as the "pitch" in the **x** direction) and a length $\mathbf{L_y}$ on the **y**-axis (referred to herein as the "pitch" in the **y** direction). Every cell **34** has the same pitches $\mathbf{L_x}$ and $\mathbf{L_y}$. It is convenient to make pitches $\mathbf{L_x}$ and $\mathbf{L_y}$ equal. Pitches $\mathbf{L_x}$ and $\mathbf{L_y}$ may differ from one another.

[0080] Figure 12 depicts a single cell **34** of reticle **30**. Cell **34** has an aperture **32** dimensioned $\mathbf{l_x}$ by $\mathbf{l_y}$. The remainder **33** of cell **34** is opaque. Figure 12 arbitrarily displays a cell **34** with the aperture **32** in its bottom left hand corner. The choice of cellular construction depicted in Figure 12 is not unique in that other cellular constructions can be envisaged.

[0081] The aperture duty cycle of reticle **30** varies along each of the **x** and **y** axes. "Aperture duty cycle" is the fraction of the area ($A = L_x L_y$) of a cell **34** occupied by aperture **32** and may be calculated as follows:

$$\textit{aperture duty cycle} = (l_x l_y)/(L_x L_y) \quad (1).$$

In a currently preferred embodiment,

$$l_x = L/3 + n_x L/(3N_x) \quad n_x = 0,1,2,\ldots N_x \quad (2)$$

$$l_y = L/3 + n_y L/(3N_y) \quad n_y = 0,1,2,\ldots N_y \quad (3)$$

where N_x and N_y are respectively the numbers of cells in the **x** and **y** dimensions of reticle **30** and n_x and n_y are respectively integer indices of the cell number in the **x** and **y** dimensions respectively. Indices n_x and n_y uniquely identify a particular cell **34** of reticle **30**.

[0082] Although the variation of l_x and l_y in preferred embodiments of the invention is described by equations (2) and (3), adherence to these equations is not a requirement. All that is required to determine the absolute position of fiber end **12'**, is that there is a known relationship between the dimension l_x and the index n_x and the dimension l_y and the index n_y, so that knowledge of the aperture duty cycle can be used to calculate the indices n_x and n_y. The simple relationships of equations (1), (2) and (3) facilitate relatively simple determination of the position of fiber end **12'**.

[0083] In Figure 11 the four corner cells (**34A**, **34B**, **34C** and **34D**) of reticle **30** demonstrate the variation of the aperture duty cycle. In cell **34A**, aperture **32A** is dimensioned such that $l_x=(1/3)L_x$ and $l_y=(1/3)L_y$, yielding an aperture duty cycle of 1/9. In the illustrated embodiment, the aperture dimension l_x varies linearly along the **x**-axis of reticle **30** from $l_x=(1/3)L_x$ in cell **34-A** to $l_x=(2/3)L_x$ in cell **34-B**. As a result, cell **34-B** has an aperture duty cycle of 2/9. Similarly, the dimension l_y varies linearly from $l_y=(1/3)L_y$ in cell **34A** to $l_y=(2/3)L_y$

in cell **34C**, yielding an aperture duty cycle of 2/9 in cell **34C**. In cell **34D**, $l_x=(2/3)L_x$ and $l_y=(2/3)L_y$, for an aperture duty cycle of 4/9.

[0084] As shown in Figures 5, 7 and 13, lens **25** projects patterns of the radiation emitted by radiation banks **21** onto reticle **30**. Figure 13 depicts outlines of the images of radiation banks **21** on reticle **30**. During each phase (**A** through **L**), a spatially-periodic pattern of radiation is imaged onto reticle **30**. In the illustrated embodiment, during each phase the pattern consists of a group of spatially-periodic stripes. Where the pulsing of phases (**A** through **L**) is multiplexed in time, only the image of one of the phases (**A** through **L**) is projected onto reticle **30** at any given time. Figure 13 illustrates the locations at which the stripes of phase **A** from radiation bank **21A** and phase **G** from radiation bank **21B** (shown shaded in Figure 13) will be projected onto reticle **30** when reticle **30** is in a particular position. The particular positions of images of phases (**A** through **L**) of radiation banks **21** on reticle **30** depend upon the current location of reticle **30**, which moves with fiber end **12'**.

[0085] In preferred embodiments of the invention, the image of each individual radiation stripe on reticle **30** is rectangular and has an elongated axis and a shorter axis. Radiation banks **21-A** and **21-C** comprise radiation stripes oriented along the **x**-axis. Radiation banks **21B** and **21D** comprise radiation stripes oriented along the **y**-axis.

[0086] In preferred embodiments of the invention each radiation bank **21** comprises three groups of stripes each of which can be pulsed together. The stripes are projected onto reticle **30**, such that the image of each stripe on reticle **30** has a length along its elongated axis that is equal to an integral number of cellular pitches and a width along its short axis that is equal to 1/3 of a cellular pitch.

[0087] In preferred embodiments of the invention, images of stripes of each phase (**A** through **L**) are spatially periodic with a spatial period equal to the cellular pitch. For example, as illustrated by the image of phase **A** (see Figure 13), the image of phases **A** through **F** each comprises a group of stripes that are periodic along the **y**-axis, with a spatial period equal to the cellular pitch $\mathbf{L_y}$ of reticle **30**. Similarly, as illustrated by the image of phase **G** (see Figure 13), the images of phases **G** through **L** each comprises a group of stripes that are periodic along the **x**-axis, with a spatial period equal to the cellular pitch $\mathbf{L_x}$ of reticle **30**. Consequently, the images on reticle **30** of individual radiation stripes of a phase (**A** through **L**) occupy the same spatial phase in adjacent cells. For example, Figure 13 shows that the individual radiation stripes in the image of phase **A** occupy the same spatial phase (i.e. **y**-position) within neighbouring rows of cells.

[0088] The projection of each spatially-periodic phase (**A** through **L**) onto reticle **30** creates a Moiré effect.

[0089] Any radiation from phases (**A** through **L**) that is transmitted through reticle **30** is collected by light pipe **43** (see Figure 7) and directed onto photodetector **24**, which produces electronic signals in proportion to the intensity of the transmitted radiation. Controller **47** uses timing information to de-multiplex the signals and uniquely determine the radiation intensity for the individual phases (**A** through **L**). Controller **47** samples the electronic intensity from each phase (**A** through **L**) and uses the sampled signals to calculate the position of the reticle **30**.

[0090] The signals measured by photodetector **24** may be normalized to remove the effects of stray radiation and intensity differences between individual REDs **11**. As shown in Figure 2, extra normalization photodetectors **27** may be located where they can detect

the full intensity of each phases (**A** through **L**) from an opposing radiation bank **21**. Since the signals measured by normalization photodetectors **27** are not blocked by reticle **30**, they may be referred to as "absolute intensities" of phases (**A** through **L**). In the illustrated embodiment, signals from four photodetectors **27** are averaged to derive the "absolute intensity" of each phase (**A** through **L**). Other types and arrangements of normalization photodetectors could also be used.

[0091] Normalization may involve subtracting an offset from each phase (**A** through **L**) to account for background stray radiation that may be measured by photodetectors **24** (see Figure 7). The amount of the offset may be determined by the signal produced by the photodetector **24** during periods t_0 when none of phases (**A** through **L**) is emitting radiation (see Figure 6). The period $\mathbf{t_0}$ may be adjusted in duration or interleaved in various ways with the pulsing of phases (**A** through **L**). In the alternative to determining a separate offset for each switching unit **22**, an average offset could be used for all of a group of switching units **22**. This is not preferred.

[0092] A second step of normalization involves determining a ratio of each phase signal **A** through **L** to the corresponding absolute intensity for the phase as measured by normalization photodetector(s) **27**.

[0093] In the following discussion of position determination it is assumed that the signals representing intensities from phases (**A** through **L**) have been normalized.

[0094] The absolute position of reticle **30** may be determined in two steps. A coarse position determining step determines the position of reticle **30** to within the area of a particular cell **34**. A subsequent fine position determining step determines the position of reticle **30** within the cell **34** identified by the coarse position determining step.

[0095] A method for determining the position of reticle **30** will be explained with reference to Figures 14A and 14B, which depict a simplified implementation of the invention having only two radiation banks **21A** and **21B**. Radiation bank **21A** has three radiation stripes (**A**, **B** and **C**) oriented along the **x**-axis. Radiation bank **21B** has three radiation stripes (**G**, **H** and **I**) oriented along the orthogonal **y**-axis. The phases (**A** through **I**) of radiation banks **21A** and **21B** each comprise one radiation stripe. Figure 14B depicts the locations at which the phases (**A** through **I**) of radiation banks **21A** and **21B** are projected on reticle **30**.

[0096] Reticle **30** is constructed as described above and has a plurality of cells **34** having a constant pitch $\mathbf{L_x}$ in the **x** direction and $\mathbf{L_y}$ in the **y** direction and a variable aperture duty cycle.

[0097] In the embodiment of Figure 14B, the image of each radiation bank on reticle **30** has the same size as one of cells **34**. Figure 15 is a close-up view of the image of radiation bank **21A** on reticle **30**. Because the dimensions of the image of radiation bank **21A** are $\mathbf{L_x}$ by $\mathbf{L_y}$ (i.e. the same as the cellular pitch of reticle **30**), the image of radiation bank **21A** overlaps a maximum of four cells. In Figure 15, the image of radiation bank **21A** overlaps cells (**34A**, **34B**, **34C** and **34D**). The image of radiation bank **21A** may overlap the apertures (**32A**, **32B**, **32C** and **32D**) in as many as four cells **34**. In Figure 15, the areas where the image of the radiation bank **21A** overlaps apertures (**32A**, **32B**, **32C** and **32D**) are designated **35A**, **35B**, **35C** and **35D** respectively.

[0098] A photodetector **24** (not shown in Figure 15) measures the intensity of transmitted radiation from each phase **A**, **B** and **C** and produces a corresponding electronic signal, which is sampled and normalized as described above. It can be seen from Figure 15 that the signal from phase **A** will be proportional to the sum of areas **35C** and **35D**. Similarly, the signal from phase **C** will be proportional to the sum

of the areas **35A** and **35B**. There will be no appreciable signal from phase **B**, since the image of phase **B** lies completely on opaque areas of reticle **30**. The sum of the signals corresponding to all three phases **A**, **B** and **C** is proportional to the sum of the areas (**35A**, **35B**, **35C** and **35D**) where the image of the radiation bank **21A** overlaps apertures (**32A**, **32B**, **32C** and **32D**) of reticle **30**.

[0099] If the sum of the signals transmitted through reticle **30** from each radiation stripe (**A**, **B** and **C**) is designated $\mathbf{I_1}$, then:

$$\begin{aligned} I_1 \propto A_1 &= A_{35A} + A_{35B} + A_{35C} + A_{35D} \\ &\approx (l_y - \Delta_y)(l_x - \Delta_x) + \Delta_x(l_y - \Delta_y) + \Delta_y(l_x - \Delta_x) + \Delta_x\Delta_y \end{aligned} \tag{4}$$

where $\mathbf{l_x}$ and $\mathbf{l_y}$ are the dimensions of aperture **32-A** and Δ_y and Δ_x represent the displacement (in both dimensions) of the image of radiation bank **21-A** from the corner of cell **34-A**. In general, equation (4) will hold true, provided that:

$$l_y - L_y < \Delta_y < l_y \tag{5a}$$

and

$$l_x - L_x < \Delta_x < l_x \tag{5b}$$

When equation (4) is expanded and the like terms collected, it can be reduced to:

$$A_1 \approx l_y l_x \tag{6}$$

The approximation in equation (6) arises because of the variation in the size of neighbouring apertures **32**.

[0100] If $\mathbf{L_x}=\mathbf{L_y}=\mathbf{L}$ and cell **34A** has the indices $\mathbf{n_x}=\mathbf{n_{x1}}$ and $\mathbf{n_y}=\mathbf{n_{y1}}$, then equations (2) and (3) may be substituted into equation (6) to yield:

$$A_1 = \left(\frac{1}{3}L\right)\left(1+\frac{n_{x1}}{N_x}\right)\left(1+\frac{n_{y1}}{N_y}\right) \tag{7}$$

[0101] Radiation bank **21-B** comprising phases (**G**, **H** and **I**) will cause the photodetector to produce similar electronic signals to those of radiation bank **21-A**. The controller may normalize those signals and generate a signal $\mathbf{I_2}$ for radiation bank **21B** in a manner similar to the determination of $\mathbf{I_1}$ for radiation bank **21A**. If the image of radiation bank **21B** overlaps a cell **34** indexed by $\mathbf{n_x}=\mathbf{n_{x2}}$ and $\mathbf{n_y}=\mathbf{n_{y2}}$. It can be seen from Figure 14-B that $\mathbf{n_{y2}}=\mathbf{n_{y1}}=\mathbf{n_y}$ and $\mathbf{n_{x2}}=\mathbf{n_{x1}}+\mathbf{N_d}$, where $\mathbf{N_d}$ is a known quantity that represents the distance between the image of radiation bank **21-A** and the image of radiation bank **21-B** as measured in the number of cellular pitches $\mathbf{L_x}$. Thus, for signal $\mathbf{I_2}$ from radiation bank **21-B**, equation (7) may be rewritten:

$$A_2 = \left(\frac{1}{3}L\right)^2\left(1+\frac{n_{x1}}{N_x}+\frac{N_d}{N_x}\right)\left(1+\frac{n_y}{N_y}\right) \tag{8}$$

The difference between signals $\mathbf{I_1}$ and $\mathbf{I_2}$, is:

$$A_2 - A_1 = \left(\frac{1}{3}L\right)^2\left(\frac{N_d}{N_x}\right)\left(1+\frac{n_y}{N_y}\right) \tag{9}$$

In equation (9) all of the quantities are known with the exception of $\mathbf{n_y}=\mathbf{n_{y1}}$. Consequently, equation (9) may be solved for $\mathbf{n_{y1}}$ and then the value of $\mathbf{n_{y1}}$ may be substituted into equation (7) to solve for $\mathbf{n_{x1}}$. As a

result, indices $\mathbf{n}_{x1}$ and $\mathbf{n}_{y1}$ are known and the absolute coarse position of reticle **30** is determined to within cell **34A** that has the indices $\mathbf{n}_{x1}$ and $\mathbf{n}_{y1}$.

[0102] Equations (5a) and (5b) represent the mathematical boundaries of cell **34A**. If Δ_y or Δ_x falls outside of the range of equations (5a) or (5b), then controller **47** will determine the coarse position of reticle **30** to be in an adjacent cell. The construction of cells with apertures in their lower left-hand corners is convenient for discussion of the invention, but is not required.

[0103] Controller **47** may be programmed to use a predetermined look-up table to directly identify the coarse position from the measured values of $\mathbf{I}_1$ and $\mathbf{I}_2$, without having to perform significant calculations for each measurement.

[0104] There are many computational techniques that can be employed by a controller to derive the coarse position from the measurements of various phases and other information that may be available to the controller. The invention should be understood to cover any such techniques. Other information available to the controller may include information about the current or previous fine position measurements, the current or previous coarse position measurements and other data, such as calibration information and system specific information.

[0105] The above description of the preferred embodiment contemplates an absolute position measurement system **210** that determines the absolute coarse position of fiber end **12'**. This absolute positional measurement involves determining the coarse position of fiber end **12'** without requiring reference information, such as a start position of fiber end **12'** or a reference signal. Although absolute position

measurement is a preferred embodiment of the invention contemplated in this disclosure, the disclosure should be understood to include relative coarse position measurement. For example, a reticle could be used with a constant pitch on two dimensions and a non-varying aperture duty cycle. In such a case, fiber end **12'** could start from a reference position and the controller could simply count the number of cells that fiber end **12'** travels from the reference position in each dimension. Such a technique would still be capable of providing the coarse position of fiber end **12'**.

[0106] The intensity of radiation from phases (**A** through **I**), which passes reticle **30** may also be used to determine the fine position of reticle **30** and fiber end **12'** within a cell **34** identified by a coarse position measurement. Figure 16 depicts ideal normalized intensity signals from phases (**A**, **B** and **C**) for the simplified embodiment of Figure 14 as a function of the displacement of reticle **30** in the **y** direction. On the signal corresponding to phase **A**, the portion of the signal between $\mathbf{y_0}$ and $\mathbf{y_1}$ represents displacements for which the image of radiation stripe **A** directly overlaps an aperture **32** having a y-dimension $\mathbf{l_y}$. The portion of the signal between $\mathbf{y_2}$ and $\mathbf{y_3}$, represents displacements for which the image of radiation stripe **A** overlaps completely an opaque area **33** of reticle **30**. Consequently, the intensity of phase **A** is near zero for such displacements.

[0107] The period of each phase (**A**, **B** and **C**) is equal to the pitch $\mathbf{L_y}$ of reticle **30** on the **y**-axis. The duty cycle of each phase (**A**, **B** and **C**) varies slightly as reticle **30** is displaced in the **y**-direction. The variation in duty cycle of the signals (**A**, **B** and **C**) is a result of the variation of the aperture duty cycle on reticle **30**. If the coarse position is known, measurement of an intensity $\mathbf{I_o}$ for phase **A** is not certain to uniquely identify the fine position of reticle **30**. For example, at displacements $\mathbf{y_5}$ or $\mathbf{y_6}$, the intensities for phase **A** are both equal to $\mathbf{I_o}$.

This ambiguity can be resolved by using information from another phase (**B** or **C**). For example, if phase **A** is measured to have intensity $\mathbf{I_o}$ and phase **B** is measured to have intensity $\mathbf{I_1}$, then the fine position of the reticle **30** on the **y**-axis is determined to be at $\mathbf{y_6}$.

[0108] In some circumstances, measurement of a particular phase (**A**, **B** or **C**) may yield a result where the signal is in the zero-derivative range (i.e. at a peak) or in the region where the signal is in a flat region (i.e. phase **A** in the region between $\mathbf{y_2}$ and $\mathbf{y_3}$). Such a measurement may yield an indeterminate result, because the direction of movement cannot be concluded from the measurement of that particular phase. If phase **A** was measured and determined to be in such a state, then one of the other phases (**B** or **C**) may be used as the principal phase to determine the fine position. A simple way to determine whether a first measured phase is in an indeterminate range is to compare the measured intensity of the first measured phase to thresholds, such as $\mathbf{I_{max}}$ and $\mathbf{I_{min}}$. For example, if the intensity of phase **A** is measured to be above $\mathbf{I_{max}}$ or below $\mathbf{I_{min}}$, then the controller may use phase **B** or **C** as the principal phase to determine the fine position. With aperture duty cycles that range from 1/3 to 2/3, at least one of the three phases (**A**, **B** or **C**) will be within the range between $\mathbf{I_{min}}$ and $\mathbf{I_{max}}$ and, therefore, sensitive to small changes in position.

[0109] Phases (**G**, **H** and **I**) may be used to determine a fine position of reticle **30** on the **x**-axis in a substantially similar manner. To ensure that the encoder can measure fine position on both axes, radiation banks **21A** and **21B** of the embodiment of Figure 14 have the elongated axes of their respective radiation stripes (**A**, **B** and **C**) and (**G**, **H** and **I**) oriented in orthogonal directions.

[0110] Due to the variation in aperture duty cycle across reticle **30**, the intensity of a given phase signal varies differently with small displacements for different coarse positions. This difference is depicted in Figures 17A and 17B, which illustrates several periods of a given phase signal in two regions of the reticle **30** with distinctly different aperture duty cycles. It can be seen that a given intensity $\mathbf{I_o}$ corresponds to a different position within the cell depending on the aperture duty cycle of that particular cell. When the aperture duty cycle is approximately 1/3 (as in Figure 17-B), a given intensity $\mathbf{I_o}$ corresponds to a fine position $\mathbf{y_1}$ within the cell, but when the aperture duty cycle is approximately 2/3 (as in Figure 17A), the same intensity $\mathbf{I_o}$ corresponds to a different fine position $\mathbf{y_2}$ within the cell.

[0111] This variation in aperture duty cycle may be accommodated by providing a separate fine position look-up table for each cell. The coarse position may be used to identify a look-up table to be used in determining fine position.

[0112] Practically speaking, in a given switch implementation, it is known that movement of fiber end **12'** is only required to be within a predetermined range, which depends on the switch geometry and the number of switching units **22** on the other "side" of the switch. Consequently, the controller can employ an "average" look-up table to determine an approximate fine position. For example, if the switch requires a range of movement of fiber end **12'** that is approximately 20 pitches of reticle **30** in any given direction, then a look-up table comprising the average of a signal in those particular 400 cells may be used to determine an approximate fine position. This approximation technique allows a significant reduction in controller resources (i.e. speed, instruction cycles and memory). The use of the average look-up table to calculate an approximate fine position is independent of the actual cell in which the fine position is being determined. For this

reason, the average look-up table technique has another advantage in that it does not require knowledge of the coarse position and may be employed concurrently (or prior to) the coarse position calculation.

[0113] In some instances (depending on controller resources and calculation time available), it may be suitable or advantageous to combine the average look-up table technique with the individual look-up table technique. A combination of these two techniques involves using the average look-up table first, to determine an approximate fine position. This initial procedure enables a rapid calculation of the approximate fine position. The coarse position may be determined as set out above. After the coarse position measurement locates reticle **30** to a particular cell, the fine position can be determined more accurately using a look-up table corresponding to that particular cell.

[0114] The preferred embodiment depicted in Figures 2, 5 and 13, differs from the simplified embodiment of Figure 14 in that:

- more radiation banks are provided (e.g. four radiation banks **21-A**, **21-B**, **21-C** and **21-D**);
- Each phase comprises a spatially-periodic group of radiation stripes (e.g. each phase (**A** through **L**) comprises either 5 or 6 stripes); and,
- The area covered on reticle **30** by the imaged phases is larger.

[0115] Adding radiation banks and increasing sizes of the images of the radiation banks on reticle **30** improves performance by providing data, which can be used to reduce the effects of any rotation of reticle **30**, shadow from fiber **12** or the fact that RED's **11** may be round and therefore may produce images on reticle **30** that are not ideal stripes.

[0116] For example, having third and fourth radiation banks facilitates measurement of rotation of reticle **30**. As shown in Figure 5, radiation banks **21A** and **21C** both comprise radiation stripes having elongated axes oriented in the **x** direction. Thus, phases from either one of radiation banks **21A** or **21C** may be used as described above to measure the fine position of reticle **30** on the **y**-axis. Rotation of reticle **30** may be measured by comparing *y*-axis positions determined using information from the phases of both radiation banks **21A** and **21C**. If the fine position measured by radiation bank **21-A** is different from that measured by radiation bank **21-C**, then reticle **30** must be in a rotated position relative to radiation banks **21A** through **21D**.

[0117] If the difference in the fine position determined using the signals from radiation banks **21A** and **21C** is δ_y and the separation between the images on reticle **30** of radiation banks **21A** and **21C** is N_d, then the angular rotation θ of reticle **30** in radians can be determined according to:

$$\theta = \sin^{-1}(\delta_y/N_d) \approx \delta_y/N_d \qquad (10)$$

[0118] In addition to measuring rotation, the larger size and larger number of the radiation banks in the preferred embodiment provide extra light intensity and a larger area of coverage on the surface of reticle **30**. The additional light and area of coverage improve the signal to noise ratio of the position measurement system **210**, which helps to overcome the practical difficulties associated with discrete RED sources and the shadow of fiber **12**. In addition, the larger size and larger number of radiation banks **21** in the preferred embodiment help to reduce the effects of surface defects, such as lithographic imperfections and impurities on reticle **30**.

[0119] The images on reticle **30** of radiation banks **21** in the embodiment of Figures 2, 5 and 13 are equal in area to two or more cells **34**. The intensity of the sum of the signals from a given radiation bank **21** is determined by the area of the apertures of the cells covered by that radiation bank image. If the area of the image of each radiation bank **21** on reticle **30** is equal to the area of an integral number of cells, then this total aperture area will be approximately constant for a range of about one pitch in each direction. For example, the sum of the phases (**A**, **C** and **E**) from the image of radiation bank **21-A** will be approximately constant for a range of up to one pitch in each direction. As described in above for the simplified embodiment of Figures 14 and 15 having two or more radiation banks **21** facilitates the calculation of the coarse position based on information available from the phases from each such radiation bank **21**. An algebraic calculation of the coarse position for the preferred embodiment with the four larger radiation banks **21** as depicted in Figures 2, 5 and 13 may be done according to the same principles used for the simplified embodiment of Figures 14 and 15. As long as the images on reticle **30** of the radiation stripes of each phase are spatially-periodic in the manner described above, then the calculation of the fine position is exactly the same in the preferred embodiment as it is in the simplified embodiment. Practically, however, it is easier to calculate the fine position in the preferred embodiment, because the signal to noise ratio can be considerably improved.

[0120] There are many possible variations of this invention. Without limitation, some of these variations provide alternative structures for a reticle. For example a reticle (not shown) may have periodic variations of aperture duty cycle on each of the x and y axes. Such a reticle is said to have multiple “chirps”. For example, the dimensions of the apertures of such a reticle could have two chirps on each dimension as described by the equations (2') and (3'):

$l_x = L/3 + 2n_xL/(3(N_x-2))$ for $n_x = 0,1,2, \ldots (N_x/2-1)$; and
$l_x = L/3 + 2L(n_x-N_x/2)/(3N_x)$ for $n_x = (N_x/2), (N_x/2+1), \ldots N_x$
(2')

$l_y = L/3 + 2n_yL/(3(N_y-2))$ for $n_y = 0,1,2, \ldots (N_y/2-1)$; and
$l_y = L/3 + 2L(n_y-N_y/2)/(3N_y)$ for $n_y = (N_y/2), (N_y/2+1), \ldots N_y$
(3')

[0121] Embodiments incorporating reticles with multiple chirps, such as the one described by equations (2') and (3'), can provide greater variation in aperture duty cycle as between adjacent cells. In this manner, it is easier for the coarse position measurement system to distinguish between immediately adjacent cells on the reticle.

[0122] In order to implement an absolute position measurement encoder using a multiple chirp reticle it is necessary to determine the chirp that the reticle presently occupies. This extra information can be obtained from a number of sources, including prior knowledge of the absolute position, the drive conditions imparted on the actuation system and a prediction of the resultant movement of the reticle. In addition, external reference sources of radiation may be used to indicate which chirp the reticle presently occupies.

[0123] Reticle **30** does not need to have cells arranged in a rectangular grid, but could have other layouts which produce Moiré interference patterns when radiation patterns are projected onto the reticle. One such embodiment has a reticle pattern as shown in Figure 19A, wherein the reticle **99** is made up of concentric annuluses of opaque material **98**. In this embodiment, the layout of radiation banks **21** may remain as a series of orthogonal radiation stripes (see Figure 5). This arrangement of radiation banks **21** still generates a Moiré

interference pattern when projected and imaged onto circularly patterned reticle **99**.

[0124] A particular advantage in the embodiment of Figure 19A is that the fiber measurement system becomes rotationally symmetric and it is no longer necessary to measure the angular rotation of reticle **99**.

[0125] Circularly symmetrical reticle **99** also provides absolute positional information over two dimensions, since the modulation level of the various phases (**A** through **L**) remains dependent on the location at which the various phases (**A** through **L**) are imaged onto the surface of reticle **99**. In some positions, the images of phases (**A** through **L**) alone will not be determinative of the absolute position. In such a scenario, controller **47** may still be able to resolve the absolute position of fiber end **12'** based on prior knowledge of the absolute position, the drive conditions imparted on the actuation system and/or a prediction of the resultant movement of reticle **99**.

[0126] In the circularly symmetrical embodiment of Figure 19, the contrast, for phases (**A** through **L**), between the lowest signal intensity and the highest signal intensity (i.e. the "modulation depth") will be less than the corresponding modulation depth of the preferred implementation, where both reticle **30** and radiation stripes are oriented in orthogonal straight lines. It is possible, however, to compensate for the lower modulation depth of phases (**A** through **L**) by employing more (or higher intensity) REDs **11**, to yield higher overall phase signal intensity and correspondingly higher signal to noise ratio at photodetector **24**.

[0127] Improved performance can be obtained from circularly oriented reticle **99**, when it is used in combination with a layout of radiation banks that is somewhat different than that of Figure 5. In the case of reticle **99**, it is advantageous to have the radiation banks, the radiation stripes and the corresponding RED's uniformly distributed, to ensure that Moiré interference is produced for all positions at which the radiation banks are imaged onto the surface of reticle **99**. One such radiation bank **97** is shown in Figure 19B. In Figure 19B, control signal REDs **11** are arranged in a grid and the multiplexing circuitry is designed such that REDs **11** can be pulsed to create radiation stripes **96A** that are oriented in the **x**-axis direction (i.e. rows of REDs **11**) or radiation stripes **96B** oriented in the **y**-axis direction (i.e. columns of REDs **11**). Because the radiation stripes are pulsed in synchronization with the system clock, the phases can still be easily extracted by photodetectors **24** and their associated controllers on the opposing side of the switch. In the layout of Figure 19B, it is relatively easy to increase the overall light level of the Moiré interference pattern by simply increasing the number of control signal RED's **11** that are employed.

[0128] In the embodiments of Figures 5 and 13, "y-axis radiation banks" **21A** and **21C** have radiation stripes are responsible for the measurement of the fine position on the **y**-axis and "x-axis radiation banks" **21B** and **21D** are responsible for measuring the fine position on the **x**-axis. It is desirable to avoid cross-coupling of control signal modulation on the **x** and **y** axes. Ideally, the radiation reaching photodetector **24** from **y**-axis radiation banks **21A** and **21C** would be unaffected by displacements of reticle **30** along the **x**-axis. However, because of discrete RED radiation sources **11** and the variation in size of adjacent apertures on the **x**-axis of reticle **30**, there is a small amount of modulation of phases (**A** through **F**) from **y**-axis radiation banks **21A** and **21C** that results from movements of the reticle **30** along the **x**-axis.

Similarly, radiation from phases (**G** through **L**) of x-axis radiation banks **21B** and **21D** may be undesirably modulated by movement of reticle **30** along the **y**-axis. This undesirable "coupling" or "cross-coupling" may be compensated for in software. The cross-coupling of control signal pahses can also be reduced or eliminated by using different embodiments of the radiation banks and the reticle.

[0129] In a first embodiment designed to reduce the cross-coupling of control signals, RED's **11** for different radiation banks have different wavelengths. In addition, this embodiment uses a reticle similar to that of Figure 11, but fabricated such that the reticle lines in the direction of the **x**-axis are made of a material that is opaque to only a first one of the control signal wavelengths, but not the other. The reticle lines in the direction of the **y**-axis are opaque to the other control signal wavelength, but not to the first control signal wavelength. This embodiment decouples the measurement of the reticle position on the **x**-axis from the measurement of the reticle position on the **y**-axis and improves the signal to noise ratio of the position measurement system.

[0130] A convenient choice for the different wavelengths is 940 nm and 830 nm, although it should be appreciated that many choices are available and the selection is based on convenient availability of RED sources **11**, the spectral response of photodetector **24** and the availability of coating materials, which may be used to make the reticle lines that will selectively block one or the other wavelength.

[0131] The operation of the dual wavelength system can be explained with reference to Figure 20. The image of a pattern of control signal REDs **11** from a particular **y**-axis radiation bank is shown superimposed over the reticle **102** as it would be if REDs **11** were imaged onto reticle **102** of a particular switching unit (not shown). For purposes of the discussion of this alternative embodiment, it is

convenient to assume that control signal REDs **11** of this particular y-axis radiation bank have a wavelength of 940 nm. Reticle **102** is comprised of lines **100** oriented along the **x**-axis and lines **101** oriented along the **y**-axis. Lines **101** are opaque to radiation at 940 nm and transmit radiation at 830 nm, while the lines **100** are opaque to radiation at 830 nm and transmit radiation at 940 nm. Figure 20 shows that the number of control signal REDs **11** that are transmitted by reticle **102** to illuminate photodetector **24** is increased considerably over the previously disclosed embodiments. This increase is a result of the transparency of lines **101** oriented on the **y**-axis to the radiation of the REDs **11** at λ=940 nm. In the previously disclosed embodiments, more radiation from control signal REDs **11** was blocked by the opaque lines of the reticle **30** oriented on the **y**-axis. The increase in the number of detectable control signal REDs **11** for the dual wavelength embodiment represents a significant gain in the intensity of the control signals at the surface of photodetector **24**.

[0132] While reticle **102** in Figure 20 is shown with regularly spaced lines (**100** and **101**), it could also be fabricated with a variation in the aperture duty cycle.

[0133] The arrangement of Figure 20 has the added advantage that movements of reticle **102** in the **x** and **y** directions are decoupled from one another. Referring to Figure 20 (and recalling the assumption that RED's **11** therein depicted are at λ =940 nm), it can be seen that, because of the transparency of lines **101** to radiation at λ=940 nm, a movement of the reticle **102** along the **x**-axis direction has no effect on the control signal transmission. Similarly (although not shown), when RED's from an **x**-axis radiation bank are imaged onto the surface of the reticle **102**, such control signal radiation will not vary with position of reticle **120** in the **y**-axis direction.

[0134] A dual wavelength reticle **102** may be made by a two-step lithography process or by fabricating the required lines on two separate substrates and bonding them together, for example.

[0135] In yet another variation of the previously described embodiments designed to decouple the **x** and **y** movements, different polarizations (rather than different wavelengths) can be utilized for each of the **x**-axis and **y**-axis radiation banks. In such an embodiment, the **y**-axis radiation banks (**21A** and **21C**) can have a polarizing material placed in front of their REDs **11**, which transmits only light of a single polarization to be projected onto the reticle. An orthogonally oriented polarizing material is placed in front of the **x**-axis radiation banks (**21B** and **21D**), so as to transmit radiation of orthogonal polarity onto the reticle. In a manner similar to that of the dual wavelength reticle **102** (see Figure 20), the reticle in the dual polarization embodiment is patterned with selectively transmitting lines of polarizing material that transmit certain polarities and block orthogonal polarities. In this manner, the control signals for the measurement of the **x**-axis and **y**-axis positions can be independently extracted without the undesirable coupling effect. This dual polarization embodiment allows the use of a single wavelength control signal RED **11**.

[0136] As will be appreciated by those versed in the art of optics, the invention disclosed here, while described in terms of a preferred embodiment based on the use of optical fibers, applies directly also to other carriers of optical beams. In this disclosure, therefore, the phrases “fiber” and “optical fiber” should be understood to include such general carriers, conduits and channels capable of carrying optical beams. In the case of an optical fiber, the end of the fiber optically behaves like the combination of a lens and an optical aperture. In a more general case, therefore, the invention applies equally well to sets of opposed optical apertures through which emerge optical beams to be

switched from any given one of the input apertures to any one of the output apertures. As with the ends of fibers manipulated by actuators in the case of the preferred embodiment, each input and output channel, in this more general alternative embodiment, is provided with an arrangement of optical elements positioned behind the associated aperture. The arrangement of elements, or an element in the arrangement, is manipulated to direct the beams between input and output apertures. Specifically a micro-machined electrostatic mirror (MEMS) device may be employed to direct the beam. In this alternative embodiment a reference pattern is kept in fixed spatial relation to the relevant directing element.

[0137] The above descriptions of the simple and preferred embodiments are intended for illustrative purposes only, and are not intended to limit the scope of the present invention in any way. Those skilled in the art will appreciate that various modifications can be made to the embodiments discussed above without departing from the spirit of the present invention.

[0138] The above described embodiment of reticle **30** having a variable aperture duty cycle is useful for determining the absolute position of fiber end **12'**. However, a reticle having both constant pitch and constant aperture duty cycle can be used to implement a position measurement system that discerns the relative position of fiber end **12'** (i.e. relative to some reference position). The invention should be understood to incorporate such embodiments.

[0139] Although the preferred embodiment discloses radiation banks having three groups of radiation stripes (i.e. three phases) in each radiation bank **21**, the number of phases in each radiation bank **21** is not limited to three. The invention should be understood to incorporate schemes having different numbers of phases in each radiation bank **21**,

provided that the images of the radiation stripes meet the size and periodicity criteria outlined above. In addition, the individual radiation stripes need not be comprised of REDs. Generally, any light source that can be shaped into a geometry able to approximate the size and periodicity criteria discussed in this disclosure may be used to form the radiation stripes and the radiation banks.

[0140] Although advantageous, the embodiment depicted in Figure 7 is not unique. There are many embodiments capable of measuring the individual radiation signals from each phase (**A** through **L**). For example, the technique of the preferred embodiment involves multiplexing the phases (**A** through **L**) in time and then measuring them using a single photodetector **24**. However, an alternative embodiment involves continuously active radiation signals from each radiation bank **21** or each phase (**A** through **L**) and a plurality of photodetectors, each photodetector shaped and aligned, so as to only receive signals from a particular radiation bank **21** or a particular phase (**A** through **L**). Another alternative embodiment involves using different wavelengths of radiation for each phase (**A** through **L**) and having distinct wavelength sensitive photodetectors or band pass filters corresponding to each phase (**A** through **L**). The invention should be understood to incorporate any means of uniquely measuring the radiation signals from each phase (**A** through **L**). It will be appreciated, however, that the preferred embodiment using time division multiplexing of phases (**A** through **L**) and a single photodetector has the inherent advantage of being able to be produced with relatively inexpensive "off the shelf" type components. Although the radiation banks **21** described above represent a particular embodiment of the present invention, there are other embodiments used in particular circumstances that may prove to be advantageous.

[0141] As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. Accordingly, the scope of the invention is to be construed in accordance with the substance defined by the following claims.